DTU Library

Design of Efficient Sound Systems for Low Voltage Battery Driven Applications

Iversen, Niels Elkjær; Oortgiesen, Rien ; Knott, Arnold; Andersen, Michael A. E.; Høyerby, Mikkel

Published in:
Proceedings of the 141st Audio Engineering Convention Convention

Publication date:
2016

Document Version
Peer reviewed version

Audio Engineering Society

Convention Paper

Presented at the 141st Convention
2016 September 29 – October 2, Los Angeles, CA, USA

Design of Efficient Sound Systems for Low Voltage Battery Driven Applications

Niels Elkjær Iversen[1], Rien Oortgiesen[2], Arnold Knott[1], Michael A. E. Andersen[1], and Mikkel Høyerby[2]

[1]*Technical University of Denmark - DTU, Kongens Lyngby, 2800, Denmark*
[2]*Merus Audio, Herlev, 2730, Denmark*

Correspondence should be addressed to Niels Elkjær Iversen (neiv@elektro.dtu.dk)

ABSTRACT

The efficiency of portable battery driven sound systems is crucial as it relates to both the playback time and cost of the system. This paper presents design considerations when designing such systems. This include loudspeaker and amplifier design. Using a low resistance voice coil realized with rectangular wire one can boost the efficiency of the loudspeaker driver and eliminate the need of an additional power supply. A newly developed switching topology is described which is beneficial to near-idle efficiency (< 2 W), which is crucial for real audio applications in the consumer electronics space. A small sized sound system was implemented using the discussed design considerations. The amplifier efficiency performance was found to be very high with near-idle efficiency reaching a remarkably 88% at 2 W. The average output SPL was estimated to be up to 90 dB in half spheric anechoic conditions. Measured results are compared with current state-of-art and shows a 14% points efficiency improvement.

1 Introduction

The efficiency of consumer electronics is an important performance parameter. Not only due to the environmental challenges the society faces but also due to the extended battery life in portable sound systems that comes with highly efficiency. In audio there is an increasing trend towards battery driven and portable sound systems. One of the big challenges for these kind of sound systems is the capability to play sufficiently loud while having a decent play back time. An immediate solution is to use larger batteries. However this will increase the cost and weight of the sound system. The optimal solution is to utilize methods to boost the efficiency of the sound system. This paper presents these methods including the design procedure and implementation of a highly efficient battery driven sound system. That includes special transducer and amplifier design. Measurements of the realized sound systems performance are provided and commented.

2 Sound system efficiency

To make an efficient audio systems the different blocks of which it consists must be considered. This essentially includes the loudspeaker, the amplifier and the power supply.

2.1 Loudspeaker

Loudspeakers are very well described in literature [1], [2], [3]. However the fundamentals of its' operation will be repeated here for convenience. The conventional loudspeaker is the moving coil loudspeaker. It consist of three essential building blocks which are coupled to one another. That is the voice coil, the magnet system and the diaphragm. Fig. 1 shows the loudspeaker driver with the three blocks highlighted. The voice coil is essentially a piece of wire turned

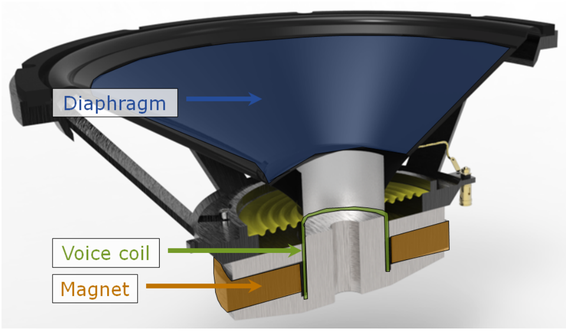


Fig. 1: Cross sectional view on a loudspeaker driver.

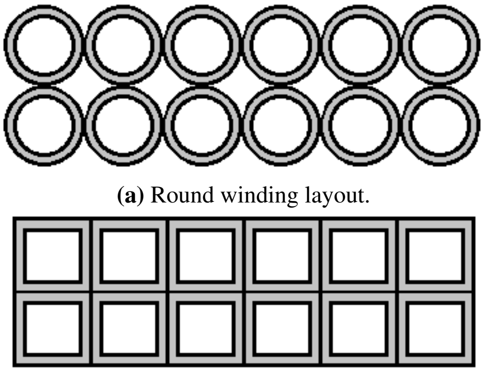
many items around the core of the magnet system. This makes it an inductor with a nominal resistance, that is the resistance at 0 Hz. This resistance is also known as the DC resistance, R_E, and conventional loudspeaker drivers have DC resistances ranging from 4-8 Ω. The loudspeaker is operating when the amplified signal from the amplifier is fed into the voice coil terminals. This will generate a current. The current will induce an electromagnetic field in the voice coil, causing a displacement due to the static magnetic field of the permanent magnet. This displacement is transferred to the diaphragm and emitted as sound. To improve the efficiency of the loudspeaker and the sound system a lower voice coil DC resistance is desired. A low DC resistance can increase the fill factor of the voice coil which is beneficial for the loudspeaker efficiency. This is discussed in [4], [5] and [6] where measurements confirms the theory that the fill factor, κ, is approximately proportional with the efficiency, η_0:

$$\eta_0 \propto \kappa \tag{1}$$

A method to obtain a low DC resistance while improving the fill factor is to use rectangular wire for the voice coil windings as it removes the tiny air gaps that exist between conventional round wire as shown in fig. 2.

2.2 Electronics

To boost the efficiency of the electronics in a battery driven sound system, which basically consists of the



(a) Round winding layout.

(b) Rectangular winding layout.

Fig. 2: Using a rectangular winding layout increases the fill factor as the tiny air gaps between the conventionl round wires are removed.

power supply and amplifier, one definitely want to utilize switch-mode technology. This technology is widely used in power electronics [7] and theoretically offers an efficiency of 100%. Previous work has shown that practical implementations can achieve efficiencies well above the 90% mark as shown in [8], [9] and [10]. In addition to this switch-mode audio amplifiers can achieve excellent performance with Total Harmonic Distortion (THD) beneath 0.005% [11], [12]. To further improve the efficiency a tracking power supply could be an option as discussed in [13].

However a simpler solution is to completely remove the power supply. This can be done with the use a low impedance load. In a previous study it has been observed that the efficiency of a battery driven sound system can be greatly improved when driving low impedance loads from a low voltage rail [14]. In addition to this it has been shown in [15] and [16] that especially near-idle losses are important for the amplifier when playing real music signals. Typically the output power of the amplifier will be in a range up 2 W when driven from a low voltage supply, that is typically less or equal to 12 V, also observed in [15]. Therefore it is relevant to use an amplifier topology that deals specifically well in this power range.

2.2.1 Amplifier topology

Such and amplifier topology is the newly developed eximo® topology, designed by Merus Audio. This topology achieves the lowest idle power consumption

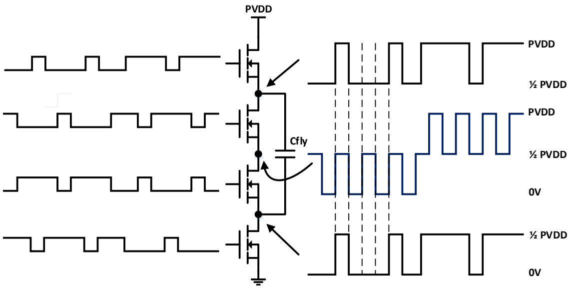


Fig. 3: Multi-level output stage.

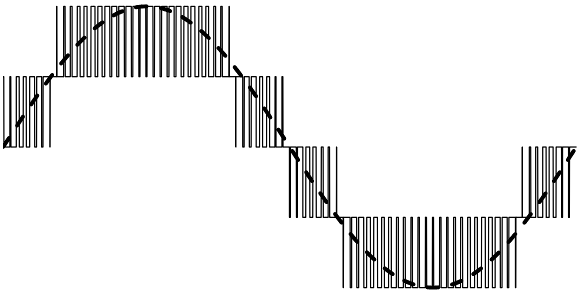


Fig. 4: Full bridge-tied load 5-level output signal when driven by a sinusoid input signal.

normalized to maximum output power [17]. Low near-idle power loss is achieved by employing multi-level switching technology which can establish multiple PWM output levels from a single supply. The half-bridge power stage that is used to establish a multi-level output signal is shown in fig. 3. A total of four MOSFETs is used in each power stage of which each MOSFET is driven by an individual PWM signal. The capacitor (C_{fly}) that is sitting in between the top and the bottom MOSFET functions as an extra supply element. One half-bridge power stage will establish a three level output signal at its switching node: 0V, 1/2PVDD, and PVDD. When combining two half-bridge power stages into a full bridge-tied load (BTL) configuration, up to five levels can be established as seen by a differentially connected speaker load, as shown in fig. 4. Note that an inherent property of a five multi level system is a quadrupling of the switching frequency at the output nodes. As a differentially connected speaker load sees a five level modulated signal it experiences significantly less out-of-band switching residuals. This implies that the amplifier can operate in a filter-less output configuration while maintaining efficiency and reducing EMI and EMC implications. The main advantage in near-

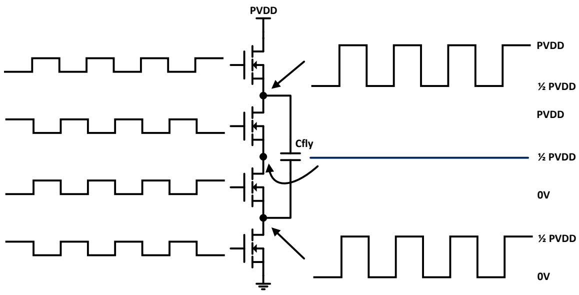


Fig. 5: Multi-level output stage.

idle operation is that the output node of the half-bridge contains close to zero switching activity due to cancellation of the individual switching nodes, as shown in fig. 5. Close to zero switching activity in near-idle operation can significantly reduce power loss in the amplifier through two main mechanisms:

- Elimination of idle conduction losses in the power stage, filter, and speaker. Both conductive and magnetic losses.
- Capacitive switching losses can subsequently be effectively reduced to scale down MOSFET switching frequency.

3 Implementation and measurements

Based on the technological overview presented above a sound system has been designed to be as efficient as possible. The implemented amplifier utilizes the described eximo® switching topology with a five level PWM modulation to boost the efficiency at low power outputs. Moreover the switching topology allows for an implementation without output filter. The system is designed to run from a low voltage supply of approximately 10 V corresponding to the available voltage from three lithium ion battery cells in series which is a typical configuration in small battery packs.

A four inch driver was implemented using a rectangular winding layout for the voice coil to increase the fill factor. The resulting DC resistance was measured to be 1.7Ω. In addition to this the small signal parameters of the implemented driver was measured with a Klippel system [18] and the results are shown in table 1. Note that the nominal sensitivity is rather low, 84 dB, compared to high efficiency drivers which can be above 90 dB. However this is expected due to the small size of the driver and the low resonant frequency of the driver which is obtained by using a rather heavy diaphragm. The low resonant frequency of the driver

Q_{TS}	V_{AS}	f_S	R_E	$SPL_{1W@1m}$	η_0
0.55	3.9L	61Hz	1.7Ω	83.6dB	0.145%

Table 1: Measured small signal parameters of implemented driver.

is beneficial for the low frequency output of the driver. The frequency response of the driver was measured in anechoic conditions and fig. 6 shows the results. The frequency response of the driver reveals that it is an extended range driver as its' pass band is from approximately 100 Hz to 7500 Hz. To emulate the application

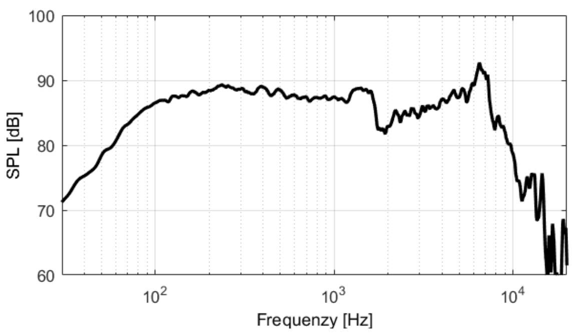
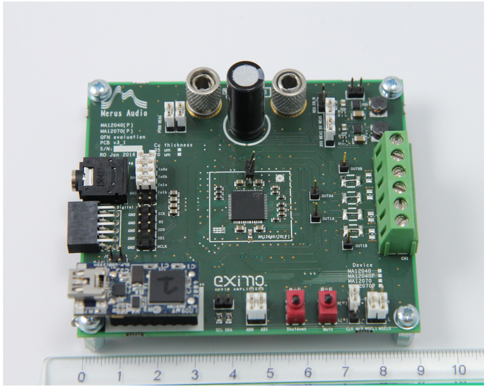


Fig. 6: On axis frequency response of implemented driver at 1.13V@40cm measured in anechoic conditions at a halfsphere environment (2π).

of a portable sound system a small vented box cabinet was designed for the driver. Vented box cabinets are well described in previous work [2], [3] and will not be elaborated here. The cabinet has a small volume of approximately 3.3 litres, making it in the same size range as commercially available portable systems. The Helmholtz resonant frequency of the cabinet is approximately 70 Hz. This boost the frequency response a little bit around 100 Hz. Fig. 7 shows the implemented amplifier, driver and speaker.

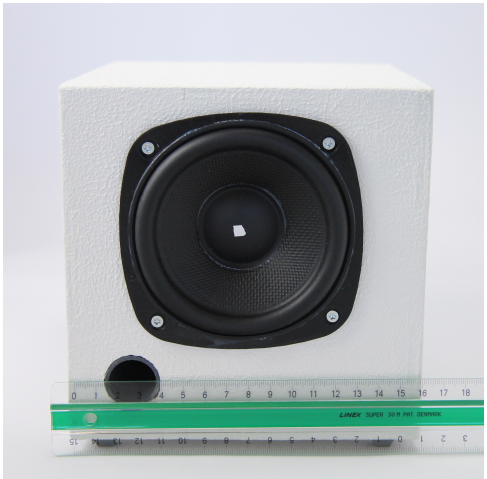
3.1 System efficiency

The efficiency of amplifier was measured when playing into the real implemented loudspeaker. The test signal used was a pink noise signal as it represents real



(a) Implemented amplifier using the eximo® switching topology.

(b) Custom made driver with $R_E = 1.7\Omega$ using a rectangular winding layout.



(c) Simple vented box cabinet designed for the custom made driver emulating the complete small battery driven sound system.

Fig. 7: Implemented amplifier, custom driver and final loudspeaker.

audio much more realistic than sine waves. This is described in [15]. Due to the complex impedance of the loudspeaker an oscilloscope was used to measure the input and output voltages and currents over a ten second window. From this the input and output power could be calculated for each measured data point. The average input and output was found by integrating over the whole window and from this the efficiency could be calculated. Fig. 8 shows the measured results of the implemented amplifier and a reference amplifier, which is widely used in the industry and considered state-of-the-art. Note that the reference amplifier has an LC output-filter and was measured using a standard measurement setup with multi meters while playing sine waves into a purely resistive load. It is seen that the implemented amplifier performs very well. At 200 mW the efficiency is at 50% and at 2 W it hits a remarkably 88%. In addition to this the results shows that the implemented amplifier performs better than the reference amplifier. At 600 mW the implemented amplifier has 14% points efficiency advantage. Note that the efficiency advantage would be even greater if the reference system used a conventional loudspeaker instead of an approximately 2 Ω load, as it would need an additional power supply to obtain the same output powers. Based on the evaluated sensitivity of the imple-

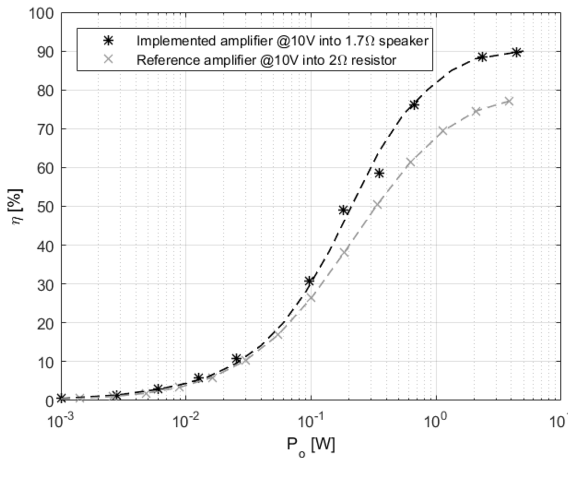


Fig. 8: Amplifier efficiency.

mented loudspeaker listed in table 1 the Sound Pressure Level (SPL) in the pass band can be evaluated for a the different input powers which allows for a plot of the SPL@1m vs. input power in a half sphere anechoic condition. The SPL can be calculated using:

$$SPL = 10\log\left(\frac{P_E\frac{\eta_0}{A}}{P_o}\right) \tag{2}$$

Where P_E is the electrical input power, $P_o = 10^{-12}$ W/m^2 is the reference acoustic sound power and A is the area of the sound surface at a given distance from the driver. A half sphere environment corresponds to $A = 2\pi r^2$, where r is the radius of the half sphere. With $r = 1$ meter we get a 8 dB reduction thus the SPL can be calculated as:

$$SPL = 10\log\left(\frac{P_E\eta_0}{P_o}\right) - 8\text{dB} \tag{3}$$

Fig. 9 shows the results including the estimated SPL for the reference amplifier. It is seen that actually very little power is required to generate a decent SPL of 80 dB for listening levels. Moreover it is seen that the peak output SPL is up to 90 dB which is rather loud. The actual SPL for real operating conditions will be even higher due to the fact that a typical operation will not be anechoic nor in a half sphere environment. Finally it is worth noticing that the implemented amplifier uses less power compared with the reference amplifier for the same SPL, especially at low listening levels.

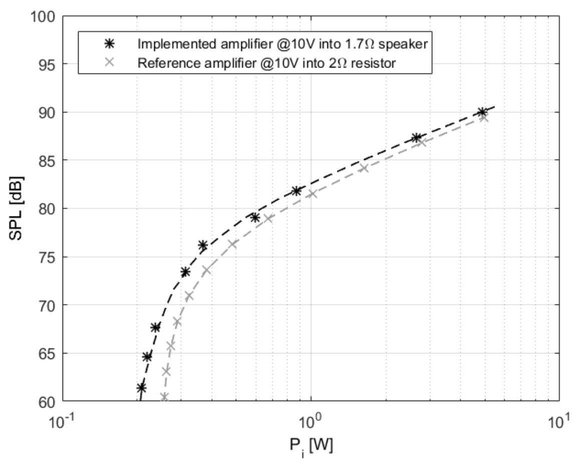


Fig. 9: Estimated output SPL@1m in a half sphere anechoic environment.

4 Conclusion

This paper has described and discussed methods to boost the efficiency in battery driven sound systems. It was found that the efficiency of the loudspeaker driver could be improve using rectangular wire with a low DC resistance for the voice coil. In addition to this it was argued that the low DC resistance can eliminate the need of a boosting power supply in battery driven applications thus improving the efficiency of the electronics. Moreover the typical output power of the amplifier was discussed and, based on previously work, found to be in the range up to 2 W. For this reason it was relevant to find an amplifier topology performing very well in this range. A new kind of amplifier topology has been described, the eximo®. It utilizes a five level modulation which boost the efficiency performance in near-idle operation.

Based on the analysis a prototype sound system has been implemented. The sound system is designed to a 10 V voltage supply corresponding to the available voltage from three lithium ion battery cells in series which is a typical configuration in small battery packs. A custom loudspeaker driver was implemented using a rectangular winding layout with a low DC resistance of 1.7 Ω for the voice coil design to boost its' efficiency. A small vented box cabinet was build to emulate the whole sound system. An amplifier utilizing the described eximo® switching topology was implemented to boost the near-idle efficiency. Measurements show a very well performing sound system with a near-idle efficiency reaching 88% at 2 W. The average output SPL was estimated to be above 90 dB at 1 meter in the pass band when operating with pink noise in a half sphere anechoic environment. In non anechoic environments this will be even louder. Moreover it was shown that very little power was needed to generate a decent SPL of 80 dB for listening levels. The measured results was compared with a reference amplifier which is widely used in the industry and considered state-of-the-art. The comparison showed that the implemented amplifier has an efficiency advantage up to 14% points and this would be even greater in conventional systems not using the custom designed low impedance speaker as they would be dependent on additional power supplies to generate the same output powers.

5 Acknowledgements

The authors would like to thank Carsten Thingaard and Morten Halvorsen from PointSource Acoustics for their assistance in the process of implementing the custom designed voice coil as well as loudspeaker driver.

References

[1] R. H. Small, "Closed-box loudspeaker systems", J. Audio Eng. Soc., Vol. 20 pp. 383-395, June 1972.

[2] A. N. Thiele, "Loudspeakers in vented boxes, Parts I and II", J. Audio Eng. Soc., Vol. 19 pp. 382-392 (May 1971); pp. 471-483, June 1971.

[3] W. Marshall Leach, Jr. "Introduction to Electroacoustics and Audio Amplifier Design", Kendall/Hunt Publishing Company, 2003.

[4] N. E. Iversen, A. Knott and M. A. E. Andersen , "Low Impedance Voice Coils for Improved Loudspeaker Efficiency", in AES Convention 139th, New York October 29th-1st November, 2015.

[5] S. Poulsen and M. A. E. Andersen , "Practical considerations for integrating switch mode audio amplifiers and loudspeakers for a higher power efficiency", in AES Convention 116th, Berlin May 8-11, 2004.

[6] N. E. Iversen, A. Knott and Michael A. E. Andersen, "Relationship between voice coil fill factor and loudspeaker efficiency", J. Audio Eng. Soc., April 2016.

[7] Erickson and Maksimovic, "Fundamentals of Power Electronics", Second Edition, Kluwer Academic Publishers.

[8] A. Yamauchi, A. Knott, I. H. H. Jørgensen and M. A. E. Andersen, "Frequency dependent loss analysis and minimization of system losses in switch-mode audio power amplifiers", in AES Convention 137th, Los Angeles, October 9-12, 2014.

[9] K. Nielsen, "Audio Power Amplifier Techniques With Energy Efficient Power Conversion", Ph.D. thesis, Volume 1, Technical University of Denmark 1998.

[10] M. Carmen, Z. Zhang, A. Knott and M. Andersen, "Power Flow Control of a Dual-Input Interleaved Buck/Boost Converter with Galvanic Isolation for Renewable Energy Systems ", Applied Power Electronics Conference 2015.

[11] S. Poulsen, M.A. Andersen, "Simple PWM modulator topology with excellent dynamic behavior", Applied Power Electronics Conference and Exposition, 2004.

[12] B. Putzeys, "Simple Self-Oscillating Class D Amplifier with Full Output Filter Control", in AES Convention 118th, Barcelona, May 28-31, 2005.

[13] A. Yamauchi, H. Schneider, A. Knott, I. H. H. Jørgensen and M. A. E. Andersen, "Investigation of Energy Consumption and Sound Quality for Class-D Audio Amplifiers using Tracking Power Supplies", in AES Convention 138th, Warsaw, Poland, May 7-10, 2015.

[14] N. E. Iversen, H. Schneider, A. Knott and M. A. E. Andersen, "Efficiency Investigation of Switch-Mode Power Audio Amplifiers Driving Low Impedance Transducers", in AES Convention 139th, New York, October 29-1 November, 2015.

[15] N. E. Iversen, A. Knott and M. A. E. Andersen, "Efficiency of Switch-Mode Power Audio Amplifiers - Test Signals and Measurement Techniques", in AES Convention 140th, Paris, 4-7 June, 2016.

[16] R. A. R. van der Zee and A. J. M. van Tuijl, "Test Signals for Measuring the Efficiency of Audio Amplifiers", in AES Convention 102th, Amsterdam, May 16-19, 1998.

[17] Mikkel Høyerby, Jørgen Kragh Jakobsen, Jesper Midtgaard, Thomas Holm Hansen, Allan Nogueras Nielsen, Hans Hasselby-Andersen, "A 270W Monolithic Five-Level Class-D Audio Power Amplifier", *2016 IEEE International Solid-State Circuits Conference*, 2016

[18] Wolfgang Klippel, "Loudspeaker Non linearities. Causes, Parameters, Symptoms", Klippel GmbH, Dresden, Germany.